(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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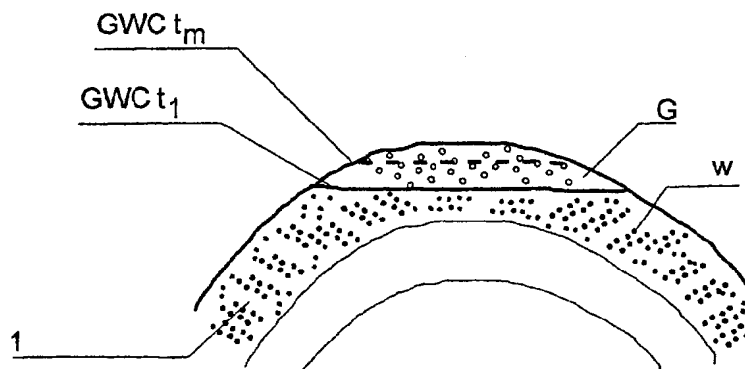
(54) Title: A METHOD FOR MONITORING SEAFLOOR SUBSIDENCE AND FOR GRAVITY MONITORING AN UNDERGROUND HYDROCARBON RESERVOIR

(57) Abstract: The invention is a method for monitoring subsidence of the sea-bed (14) of a survey area (8) caused by compaction of an underground hydrocarbon reservoir (1), and comprises the following steps: Conducting at least two series $(S_1, .., S_i, .., S_m)$ of time-indexed depth measurements (13a,.., 13n), with separation in time Δ between the measurement series characteristic of a significantly detectable long-term change of seafloor elevation due to compaction to take place in the reservoir. Measurements are time-indexed and corrected for tidal depth variations. Depth measurements (13) are conducted on survey stations (2) arranged on benchmarks (6) which have settled in the locally consolidated seabed (14). To handle short-term depth variations several stationary time-indexed short-time local reference depth measurement series (19r) are conducted at short-term local reference stations (18r) at benchmarks (6) during each separate measurement series (S_i). The reference depth measurement series (19r) are continuous for correcting each depth measurement (13) for short-time tidal depth variations occuring during each separate measurement series (S_i). To monitor compaction or seafloor subsidence during the series of measurements, the depth measurements (13, 19r) are conducted relative to a depth measurement (13r) during each series (S) at reference station (9) arranged on the seabed (14r) at a distance from the reservoir (8) being sufficiently far to be unaffected by long-term effects taking place due to compaction in reservoir (1).

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A METHOD FOR MONITORING SEAFLOOR SUBSIDENCE AND FOR GRAVITY MONITORING AN UNDERGROUND HYDROCARBON RESERVOIR.

Technical field of the invention.

The invention concerns a method and an apparatus for
5   monitoring fluid movements and seafloor subsidence/reservoir
compaction in hydrocarbon-producing fields by repeated
relative seafloor gravity and depth measurements. Monitoring
of hydrocarbon reservoir changes (as saturation, pressure,
and compaction) during production is traditionally done by
10 well measurements integrated through dynamic reservoir
modelling. Geophysical techniques for measuring changes
between the wells has emerged as useful technology in recent
years, particularly repeated seismic measurements. The
benefits of such observations and improved understanding of
15 the reservoir behaviour during production are many: among
others to optimize production / reservoir management,
optimizing drilling of infill wells and improving estimates
of remaining reserves.

Technical background, state of the art.
20   A new system comprising an instrument for use in
seafloor gravity observations has been designed and
deployed. The system is called "Remotely Operated Vehicle
Deep Ocean Gravimeter" (ROVDOG). The aim of the project was
to perform repeated measurements of gravity and pressure in
25 an oilfield to monitor the development of the reservoir. The
actual field in question is the Troll field in the North
Sea. Because of the requirement for accurate location of the
measurement points (each to within one cm of the previous
observation) a gravimeter was required which could be
30 handled by the arm of an ROV and placed atop sea floor
benchmarks. Such an instrument has been designed around a
Scintrex CG-3M land gravimeter. Motorized gimbals within a
watertight pressure case are used to level the sensor. An
assembly of 3 precise quartz pressure gauges 22 provides
35 pressure measurements which can be transformed to depth
information. The instrument may be operator-controlled via a

serial datalink to the ROV. A view of the data stream for
recording can be monitored. In one embodiment of the
invention, the serial datalink is according to the RS-232
standard. In a test run of the system, the instrument was
5   first deployed in the Troll field during June 1998. A total
of 75 observations were made at 32 seafloor locations over a
period of 120 hours. The repeatability figure of merit is
0.027 milliGal for the gravity measurement and 2 cm for
pressure-derived heights.

10 Scope of work.
       The Troll field licence partners decided in 1996 to try
to perform measurements on the Troll field in order to
montitor changes caused by the gas production and the influx
of water from the aquifier in particular. Among different
15 solutions comprising well monitoring and repeat seismic
monitoring to perform such measurements, repeated gravity
measurements on the sea floor above the field was proposed
by the inventors. In an internal study in 1997 the changes
of the gravity field were identified as comprising the
20 following factors:
       I)   water influx in the gas reservoir;
       II)   seafloor subsidence; and
       III) gas density reduction.
       I) The expected increase in gravity caused by water influx.
25 II) The expected seafloor subsidence due to reservoir
compaction. This seafloor subsidence will cause a change in
the gravity field, as measured at the seafloor, being
proportional to the subsidence, due to the vertical gradient
of the Earth's gravity field. Thus it is necessary to
30 monitor the gravity changes or "the gravity signal" to
within a resolution of the gravity corresponding to an
elevation difference of a few centimeters.
       III) Gas density reduction will give a reduction of the mass
density of the reservoir, causing a reduction of the gravity
35 field, i.e. of opposite sign with respect to gas/water rise.
       Fujimoto et al. in "Development of instruments for
seafloor geodesy", Earth Planets Space, vol. 50, pp. 905-
911, 1998, describes instruments for monitoring differential

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displacements across a fault zone in the seabed, and examines their resolutions through seafloor experiments at relatively short baselines. The horisontal differential displacement is measured by an acoustic ranging system using a linear pulse compression technique being able to measure distances on the order of 1 km between markers with an accuracy of 1 cm. The leveling or vertical displacement monitoring of the seabed is planned to use an array of ocean bottom pressure gauges and an ocean bottom gravimeter to detect differential vertical motion. The system is estimated to have a resolution of several centimeters in vertical displacement. Fujimoto et al describes how ocean bottom pressure measurements can be used in two ways to detect vertical movements of the seafloor. An ocean bottom pressure array acts as a monitoring system of relative vertical movements. Variations of atmospheric pressure are mostly compensated at the sea surface. By simulating pressure and gravity one can discriminate between a pressure change due to vertical seafloor displacements and a pressure change due to vertical sea surface displacements:

Consider the seafloor rising by 1 cm. The pressure value will decrease by 1 cm of water column. Gravity will decrease by 2.2 microGal (-3.068 microGal due to height change and +0.864 microGal due to reduced gravitational attraction of the global sea water).

Next, Consider the sea surface lowering 1 cm. The pressure in this case will also decrease by 1 cm of water column. The gravity in this case will increase by 0.432 microGal due to the reduced gravitational attraction of the local seawater.

In both of the above mentioned cases, pressure monitored at the seabed decreases, but the gravity changes differently. If measurements are performed with high accuracy, simultaneous measurements of pressure and gravity can discriminate between the two effects: sea surface level change and seabed level change.

Fujimoto et al. do not propose any method for monitoring changing parameters representing density and/or mass distribution of an underground sub-sea reservoir by

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means of gravimetric measurements with a gravity sensor on
the sea-bed. Fujimoto proposes conducting series of relative
gravimetric measurements with a gravity sensor and relative
depth measurements with a depth sensor on survey stations
5   arranged on a benchmark having fixed vertical position
relative to the local sea-bed in a survey area over a
suspected fault zone, the gravimetric measurements being
relative to gravimetric measurements and depth measurements
taken on a reference station on land. Fujimoto proposes
10 correcting the relative gravimetric measurements for the
corresponding relative depth measurements, producing
corrected relative gravity values. The corrected gravimetric
values are then used for interpreting seabed vertical
motions, and not used for comparison between series of
15 observed corrected gravimetric values with later series of
observed corrected gravity values and interpretion of a
difference of corrected gravimetric values in terms of a
change of parameters representing density and/or mass
displacement in the underground sub-sea reservoir. Although
20 seabed subsidence monitoring over the reservoir zone is one
major issue of the present invention, the gravity change
represented by seabed subsidence is noise with respect to
detecting gravity changes due to mass movements and density
change in the reservoir. Thus, in the present invention, the
25 gravity measurement due to seabed subsidence (or rise) must,
in addition to tidal and drift corrections, be corrected for
by corresponding water column pressure changes at the
seabed.

Presentation of relevant known art.
30   Gravity monitoring has previously been applied in
exploiting hydrothermal energy (Allis, R. G, and Hunt, T.
M., Geophysics 51, pp 1647-1660, 1986: *Analysis of
exploitation-induced gravity changes at Wairakei geothermal
field.*; San Andres, R. B, and Pedersen, J. R., Geothermics
35 22, pp 395-422, 1993, *Monitoring the Bulalo geothermal
reservoir, Philippines, using precision gravity data.*), and
in volcanology (Rymer, H. And Brown, G. C., J. Volcanol.
Geotherm. Res. 27, pp. 229-254, 1986, *Gravity fields and the*

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*interpretation of volcanic structures, geological
discrimination and temporal evolution.).* Recently, efforts
on measuring gravity differences above hydrocarbon fields on
land have been reported (Van Gelderen, M., Haagmans, M. R.,
and Bilker, M., Geophysical Prospecting 47, pp. 979-993,
1996, *Gravity changes and natural gas extraction in
Groningen).* For offshore fields, gravity monitoring has been
initiated in a case known to us (Hare, J., Ferguson, J. F.,
Aiken, C. L. V., and Brady, J. L., 1999, *The 4-D
microgravity method for waterflood surveillance: A model
study for the Prudhoe Bay reservoir, Alaska.),* with
measurements being performed from the surface of the ocean
ice, a non-actual situation for most hydrocarbon fields in
question. The relatively small gravity changes expected due
to reservoir parameters as compared to the gravity
variations due to noise and external variations as tides and
diurnal gravity variations, requires better accuracy than
has been achieved in marine geophysical surveys to date.

Existing underwater gravity meter systems are based
upon lowering the gravity instrument from a ship (LaCoste,
1967; Hildebrand et al., 1990). Other systems make use of
manned submersible vessels for taking measurements from
within the crew compartment of the submersible vessel
(Holmes and Johnson, 1993; Cochran et al, 1994, Evans, 1996;
and Ballu et al., 1998). The problem of relocating the
gravity meter observation point relative to the seafloor to
within approximately 2 centimeters in the vertical line, is
pronounced in the attempts of using a gravity meter inside a
manned submersible vessel. The method is also slow in
operation, and highly expensive, and running a manned
submersible vessel may pose a risk to the crew. Wave action
on the vessel is another noise acting on the gravity meter,
and so is the noise due to inadvertent movement of the crew.

Actual problems implied with the known art.

Gravity measurements taken on a surface ship or inside
a submarine in motion require absolute velocity and course
determination in order to perform an Eötvös correction.
Shipborne measurements of gravity are notoriosly noisy due

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to the ship's accelerations from sea waves and wind, so the
measurements must be low-pass filtered over long periods.

General navigation problems makes repeat measurements
made by submarine or ROV uncertain with respect to position
5   and elevation. The elevation uncertainty depends on the
uncertainty of horisontal position and the local inclination
of the seabed. The position and elevation problem of the
known art is remedied by the present invention.

Another problem is represented by the generally
10 unconsolidated sedimentary seabed surface. The
unconsolidated sedimentary surface gives inconsistent
subsidence of the gravity measurement package, either being
a bottom gravity meter lowered in a cable from a ship or set
out by an ROV, or measurements taken from inside a manned
15 submarine resting on the seabed.

Drift of the gravity meter requires frequent
reoccupations to the reference station. Thus the long
transport time to a land-based reference station makes
frequent returns to a land-based reference station
20 unfeasible.

Use of a sea-bed reference station in a shaft near the
seabed would not solve the problem with gravimeter drift of
the field instrument being carried around by an ROV.

25 **Solution to the problem and reference to the claims.**

The above-mentioned problems are largely reduced by a
method for depth measurements and monitoring of a seabed
subsidence due to compaction in a hydrocarbon reservoar
according to the invention defined in the attached set of
30 claims.

The method according to the invention removes the need
for making an Eötvös correction for vessel speed and vessel
course of the gravity measurements because the measurements
according to the present method are made stationary at the
35 seabed. The measurement of gravity and depth are done
stationary, thus no velocity corrections are needed.

The method according to the invention using measurement
stations on preinstalled benchmarks removes the measurement
position uncertainty of position reoccupation to within the

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small area of the top surface of the benchmark, thus also
removing a significant portion of the uncertainty of
elevation reoccupation due to seabed inclination, by the
same means.

5   The method according to the invention using measurement
stations on preinstalled measurement stations on benchmarks
reduce the problems with "rapid" subsidence of the
measurement vessel sinking in the loose sedimentary seabed
due to the softness and unstability of the upper

10   unconsolidated layers of the sediments. Heavy benchmarks
which are perforated and made in concrete are preinstalled
at the seabed and left to settle in the sediments for
several weeks or months before a first series S_1 of gravity
and depth measurements. By this, two essential problems are

15   solved:

        (a) The elevation of the measurement station (with
        respect to the local consolidated seabed, not with
        regard to the earth's gravity centre) is constant to
        within millimetres during a series of measurement

20   series S_1 ,S_2 ,..., S_n taking place during several
        months or years.
        (b) Vertical (and possibly horizontal) acceleration
        experienced during to slow sinking and slow settling of
        the measurement vessel in the local unconsolidated

25   sediments may explain the gravity phenomenon described
        in Fujimoto et al., see Fig. 5 and the text at p. 910,
        at the bottom of the left column.
The measurement stations at preinstalled benchmarks
according to the present invention prevents such sinking and

30   settling accelerations during the measurement at each
particular station.
        The method according to the invention using a reference
station at the seabed in the vicinity of the survey area 8
makes the return time to the reference station on the order

35   of hours. Reoccupying a reference station onshore, as done
in the known art, requires returning the gravity vessel from
the seabed to the surface and making a gravity measurement
either on land or at shallow depth.
        All transport may incur mechanical stress that may

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change the instrument's drift rate.

In the known art, the depth or pressure sensor is arranged on the submarine's outer hull surface or other places which may not be exactly of the same relative depth

5   with respect to the gravity sensor. According to the present invention, the depth or pressure sensor is arranged in the same elevational position with respect to the gravity sensor, the pressure sensors being arranged on the outside of the gravity sensor water-tight pressure housing. Thus the

10 relative depth between the gravity sensor and the pressure sensors should be repeatable within far less than 1 cm, depending only on the tilt of the water-tight housing resting on the station on the benchmark.

None of the existing systems are capable of meeting the

15 geophysical accuracy, operational speed and economical requirements of the task presented by the actual monitoring of a subsea gas reservoir, together with the need to precisely relocating the gravity instrument on the seafloor. On this background, the inventors came up with a new method

20 and a new instrument according to the invention, solving the problems of the disadvantages of the known art.

Short description of the drawing figures.
Fig. 1a illustrates the pressure and gravity sensor package connected to an ROV, further connected to a surface ship.

25 Fig. 1b illustrates a seafloor geophysical setting, with seafloor subsidence occuring at long term, and with an underground reservoir to be monitored.

Fig. 1c illustrates a modeled gravity field change due to a change in a reservoir.

30 Fig. 2 illustrates a setup of instrument stations at benchmarks at the seabed.

Fig. 3 illustrates subsidence of the seafloor and illustrates a method of monitoring seafloor subsidence, and a corresponding gravity and depth parameter measurement

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matrix built up during a long-term series of measurements.

Fig. 4 illustrates a benchmark according to the invention, for installation on and settling into the seabed sediment surface.

5   Description of the preferred embodiment.
Mechanical system.
        The preferred embodiment of the gravity and pressure sensor system is shown in Fig. 1a and comprises a sea-floor deployable system 1 having a gravity sensor system 3
10   comprising a gravity sensor 10 in a water-tight pressure housing 34 provided with thermal isolation 35. A double-gimbal frame 36 comprise two orthogonally arranged gimbal frames 36x and 36y supporting the gravity sensor housing 34 free to swing +/- 8 degrees about an x-axis 37x and +/- 9
15   degrees about a y-axis 37y. Thus a tilt of +/- 12 degrees is allowed about the x-y coordinate diagonal axis. This given freedom to swing about two orthogonal axes has proved sufficient for the tilts encountered in a field test illustrated in Fig. 1b showing the gravity sensor system 3
20   placed on a benchmark 6 arranged on a local sea-bed station 14a, ..,14n in a survey area 8, or a reference station sea-bed 14r. The preferred embodiment of the benchmark 6 will be described below. One or more depth sensors 12 are arranged outside the pressure housing 34 for a fixed relative
25   elevation in their operational position on the station 2,9 with respect to the gravity sensor 10.

The method according to the invention; subsidence.
        A method is illustrated in Fig. 1b and also in Fig. 3, for monitoring subsidence of the sea-bed 14 of a survey area
30   8 caused by compaction of an underground hydrocarbon reservoir 1. The method of the invention comprises the following steps:
*   Conducting at least two series $(S_1,..,S_m)$ of depth measurements, each series S_i comprising at least one time-
35   indexed depth measurement 13a,13b,.. ,13n. Depth mesurement $13a_1$ is conducted at a seabed station 2a during measurement

series S_1; measurement $13b_1$ is conducted on station 2b during
series S_1, depth mesurement $13a_2$ is conducted at seabed
station 2a during measurement series S_2, and so on. A separation in time Δt between at least two of the measurement

5   series $(S_1, .., S_i, ., S_m)$, i.e. at least the time between the
first and the last series S_1 and S_m should be characteristic
of a significantly detectable long-term change of seafloor
elevation, possibly due to compaction, to take place in the
reservoir 1, if such a change occurs. The tidal measurements

10 should be time-indexed in order to be corrected for tidal
depth variations which will be described below. In practice,
the depth measurements are conducted by measuring the
absolute pressure, being proportional to the weight of the
unit area water column and the air column above the pressure

15 sensor. A clock (16) may time-index each depth measurement
13 or preferably each gravity measurement 11 described
later, for tidal, drift and reference corrections of the
measurements.
    *   The top of the seabed may be very loose and

20 unconsolidated, being a bad basis for gravity measurements.
In this method, it is necessary to take depth measurements
13a,13b,..,13n relative to the locally consolidated seabed,
i.e. the seabed which is stable relative to the immediately
underlying geological consolidated ground. To achieve

25 structurally stable survey stations 2a,2b,..,2n, these are
arranged on benchmarks 6a,6b, ..,6n, the benchmarks
preferably built in concrete, arranged at the seabed. Such
benchmarks are illustrated in detail in Fig. 5, and are also
illustrated at the seabed in Figs 1b, 2 and 3. Each depth

30 measurement 13a,13b,..,13n is conducted on such a survey
station 2a,2b,..,2n arranged on a benchmark 6a,6b, ..,6n.
Each benchmark is having fixed vertical and horizontal
position relative to the local sea-bed 14a,14b,..,14n. Even
though the very top of the sedimentary layers may be loose

35 and unconsolidated, each benchmark according to the
invention may sink to settle, and will be consolidated in
the sediments before commencement of the first measurement
series S_1.
    *   Short-term depth variations comprises the effects of

tides, local currents and air pressure variations. In order
to handle short-term depth variations during a measurement
series S_i, at least one stationary time-indexed short-time
local reference depth measurement series 19r may conducted

5   at a short-term local reference station 18r at such a
benchmark 6. Preferably there are several such measurement
series 19r being conducted during each separate measurement
series S_i. The stationary short-time local reference depth
measurement series 19r are preferably continuous, and are

10 used for correcting each depth measurement 13a,13b,..,13n
for short-time (e.g. tidal) depth variations occuring during
each separate measurement series S_i.
        *   In order to monitor compaction or seafloor subsidence,
the depth measurements 13,19r are conducted relative to at

15 least one depth measurement 13r at a reference station 9 ar-
ranged on the seabed 14r outside the survey area 8. This
reference depth measurement is taken at least once during
each measurement series S_1. The reference station 9 must be
arranged at a distance from the reservoir 8 far enough to

20 being unaffected by long-term effects taking place due to
seabed subsidence or compaction in the reservoir 1 during
the series of measurements $S_1,..,S_m$, but near enough both
with respect to depth and distance to be reached within
reasonable time during each series of measurements, and

25 situated at a depth comparable to the depth of the survey
area to reduce the depth span and most of all to reduce
drift of the gravity meter and to avoid uncertainty with
respect to ground density for gravity elevation corrections.
        *   The seafloor subsidence may be monitored as a

30 difference of relative depth values Δd or $15_2, ..,15_m$ having
occured during the time Δt and interpreted in terms of
compaction in the reservoir 1.
        In a preferred embodiment of the invention, the
stationary short-time local reference depth measurement 19r

35 series is conducted by at least one separate depth meter 17r
arranged at at least one survey station 18, which may be at
least one of the survey stations 2 in the survey area 8.
The instrument 17r measuring the reference depth measurement
series 19r is preferably a continuously registering and

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logging depth meter. The measurements 19r may be used for tidal corrections. Predicted or calculated tidal corrections without local measurements may not be sufficiently accurate for use in the method of the invention. In a preferred
5   embodiment of the invention, preferably three separate depth meters $17r_1$, $17r_2$ and $17r_3$ are spread at separate short-term reference stations $18r_1$, $18r_2$ and $18r_3$ distributed over the survey area 8 to monitor the tidally and geographically varying series of depth measurements 19r. The three separate
10 continuous and time indexed depth measurement series $19r_1$, $19r_2$, $19r_3$ may be used with a tidal model for interpolating the local tidal depth for correcting each time-indexed depth measurement 13 at each station 2.

Preferably, at least one stationary short-time local
15 reference depth measurement 19r series is conducted at a short-term local reference station 18r being identical to or co-located with the reference station 9 arranged on the seabed 14r outside the survey area 8.

Gravity combined with depth measurements:
20   Having the depth measurements available for controlling or monitoring the gravity effect of the sea-water masses and of the seafloor subsidence, monitoring parameters representing density and/or mass distribution in an underground sub-sea petroleum reservoir 1 is possible by
25 means of gravimetric measurements 11 with a mobile gravity sensor 10 as described above, for use with an ROV 5 on the sea-bed 14 of a survey area 8 covering the petroleum reservoir 1. The novel features of the method according to the invention are the following steps comprising gravity
30 measurements:
*   Including, during the same measurements series $S_1, .., S_m$, relative gravmetric measurements 11a,11b,..,11n, preferably acquired simultaneously with the depth measurements 13a,13b,..,13n.
35 *   Each gravity measurement 11a,11b,..,11n is conducted on essentially the same survey station 2a,2b,..,2n arranged on the benchmarks 6a,6b, ..,6n as for the depth measurements 13a,13b,..,13n.

*   The gravity measurement 11 is conducted relative to at least one pair of reference gravity measurement 11r and a reference depth measurement 13r or 19r at a reference station 9 or 18.

5   *   The relative gravimetric measurements 11 are corrected for the corresponding long-term and short-term relative depth measurements 13 or 19r and provides depth corrected relative gravity values 21a,21b,..21n.

*   The relative gravity values 21 are corrected for the
10 effect of seabed subsidence $15_2, .., 15_m$ as calculated on the basis of the relative depth measurements 13a,13b,..,13n during the long-term time Δt.

*   The difference of depth corrected relative gravity values Δg or $\Delta 21_2, \Delta 21_3, .., \Delta 21_m$ having occured during the
15 long-term time Δt may be interpreted in terms of parameters representing a mass density change and/or a mass displacement in the reservoir 1.

The time interval Δt between at least the first and the last measurement series may be on the order of months, one
20 year or longer time. In order to monitor gravity effects, the separation in time Δt between the measurement series $S_1, .., S_m$ must be sufficient for or characteristic of a significantly detectable change of gravity Δg to take place in the reservoir, the change of gravity being due to a
25 change of mass density. Such a long time span would normally be the same as for a significantly measurable seafloor subsidence to take place, but is no limiting condition for the gravity method to work. A significantly detectable change of gravity Δg may be imagined to take place due to a
30 density change or fluid movement occuring in the reservoir, without any significantly measurable seafloor subsidence or even seafloor rise due to other geological processes.

Each gravity measurement 11a,11b,..,11n is conducted with the gravity and depth sensors 10,12 placed on a survey
35 station 2a,2b,..,2n. The survey stations are arranged each on their benchmark 6a,6b, ..,6n having fixed vertical and horizontal position relative to the local sea-bed 14a,14b,..,14n. The benchmarks are arranged in known and marked positions on the seabed in sufficient time before the

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gravity survey series $S_1, .., S_m$ for the benchmarks to settle
firmly and stably at the seabed. One preferred embodiment of
a benchmark 6 is shown in Fig. 4. The benchmark 6 has a
skirt below the outer periphery, and a somewhat elevated top

5   surface constituting the survey station 2. The baseplate of
the benchmark 6 is perforated in order for water and loose
sediment to be pressed through the benchmark during the
settling in the sediments. The benchmark is made in concrete
and is arranged to sink into the sediment leaving at least

10 the elevated top surface above the sediments when settled.
*   The gravity and depth measurement 11,13 are made
relative to at least one gravity and depth measurement
11r,13r at a reference station 9 arranged on the seabed 14r
outside the survey area 8. This is illustrated in the

15 simplified Fig. 2. The reference station 9 is far enough to
be unaffected by gravity effects taking place due to mass
changes in the reservoir 1, e.g. due to an elevating
gas/water contact GWC or an elevating oil/water contact OWC.
A modelled example of the relative gravity effect of a 10

20 metres uplift of the gas/water contact in the Troll
reservoir is shown in Fig. 1c. The relative gravity values
are shown in microGals. One can see that the gravity image
is a smoothed image of the reservoir contour. The station
grid has a spacing of about 4 km, with the stations 2

25 indicated by crosses.
       The relative gravimetric measurements 11 must be
corrected for the corresponding relative depth measurements
13 producing depth corrected relative gravity values
21a,21b,..,21n.

30   In order to discriminate a gravity effect due to
subsidence from gravity effect due to a mass density change
and/or a mass displacement in the reservoir 1, the relative
gravity values 21 shoud be corrected back to a datum plane,
for the effect of seabed subsidence $15_2, .., 15_m$ as calculated

35 on the basis of the relative depth measurements
13a,13b,..,13n during the time Δt. This subsidence
measurement and correction is illustrated in Fig. 3. The
datum plane illustrated is a plane through the reference
station 9 at the seabed 14r outside the survey area 8, but

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other datum planes closer to the stations 2 may serve the
correction purpose better.

   After correcting the gravity values 11 for subsidence
measurement, one can interpret a difference of depth
5   corrected relative gravity values Δg or $\Delta 21_2, \Delta 21_3, .., \Delta 21_m$
having occured during the time Δt in terms of parameters
representing a mass density change and/or a mass
displacement in the reservoir 1. This displacement is
illustrated in Fig. 1b by the gas/water contact from the
10   first series S_1 being indicated by $GWCt_1$ and the gas/water
contact from the second series S_m being indicated by $GWCt_m$.
This rise of GWC may be calculated iteratively until the
modelled gravity change fits the measured gravity change, or
may be inversely modeled directly from the data. The density
15   change at the gas-water contact level may also be inferred
from two-dimensional spatial deconvolution of the seafloor
gravity data. Several methods for modeling of gravity data
are known from the literature, and such methods are not
described in detail here.

20   During each and every measurement series S_1, S_2, .., S_m
the gravity sensor 10 and the depth sensor 12 are arranged
with a fixed relative elevation in their operational
position on the station 2,9. This is made practical by
arranging the depth sensors 12 on the outside the pressure
25   housing of the gravity meter as illustrated in Fig. 1a.
   The gravity sensor 10 and the depth sensor 12 are
carried by means of an ROV 5 from one station 2, 9 to
another station 2, 9 between one pair of a relative
gravimetric and depth measurements 11,13 and the next pair
30   of a relative gravimetric and depth measurement 11,13 in one
measurement series S. By using a cable-powered ROV 5 there
is no limit to the size of the survey area.
   According to a preferred embodiment of the invention,
in order not to disturb the sensors, particularly the
35   gravity sensor, the ROV 5 separates from and leaves the
gravity sensor 10 (and the depth sensor 12) before the
commencement of each relative gravimetric measurement 11 in
order not to affect the gravimetric measurment 11.

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According to the preferred embodiment, the relative gravimetric measurement 11 from the gravity sensor 10 and the depth measurement 13 from the depth sensor 12 are transferred from the unit 4 to the ROV 5 via a "ROVDOG"
5   umbilical cable 53.

According to the preferred embodiment, the relative gravimetric 11 and depth measurements 13 are transferred via an ROV umbilical cable 51 to a surface vessel 7. By this arrangement the crew can monitor online and control the
10   sampling of gravity and depth data.

The gravimetric measurements 11 are time-indexed and corrected for the gravity sensor's 10 drift with respect to time by other time-indexed gravimetric measurements 11, 11r taken before and/or later with the same gravity sensor 10 at
15   a survey station 2 or reference station 9 during the same actual period of time t_i, giving drift-corrected gravimetric measurements 11_t for further processing to produce corrected gravity values 21. The advantage by the present method is that the reference station may be reoccupied often during
20   the survey. In this way the drift rate of the gravity meter can be monitored.

According to a preferred embodiment of the invention, the depth measurements 13 arise from pressure measurements 23 converted according to the actual water density, the
25   depth sensors 12 actually being pressure sensors. Optionally, a measured water density distribution depth profile is taken into account.

A tidal water correction can be made for the corresponding relative depth measurements 13 on each series S_i of the
30   gravimetric measurements 11 in order to obtain corrected relative gravity values 21. The tidal water correction can be made theoretically on the basis of tidal modelling, or based upon gravity measurements during reoccupation of reference stations 9 or gravity stations 2.

35   Further description of the mechanical structure.

Each gimbal frame 36x, 36y is driven by an actuator 38x, 38y. The actuator 38x may rotate the gimbal frame 36x about the x-axis 37x, and the actuator 8y is arranged to

17

rotate the gimbal frame 36y about the y-axis 37y. Each
actuator 38x, 38y comprises a DC motor-driven lead screw
80x, 80y whose position is monitored by a linear
potentiometer 82x, 82y. Each linear potentiometer 82x, 82y

5   gives a readout 83x, 83y which is transmitted via a signal
conductor 84x, 84y to a control device 88 arranged to
control the actuators 8x, 8y.
Electrical system.
        Control of the system is overseen by a microcontroller

10 30 (Z-World model BL1700) being a single-board computer
comprising four serial ports, 10 12-bits A/D converters, and
64 digital I/O lines. The A/D channels are arranged to
monitor signals comprising the following:
    a)   A temperature signal 61 from a temperature sensor 60;

15 b)   A sensor coarse tilt signal 65 from a coarse tilt
          sensor 64;
    c)   A sensor fine tilt signal 69 from a fine tilt sensor
          68;
    d)   An ambient temperature signal 71 from a temperature

20   sensor 60;
    e)   Gimbal orientation sensor signals 73x, 73y (different
          from the signal 83x, 83y mentioned above) from gimbal
          orientation sensors 72x, 72y giving the orientation of
          gimbals 80x, 80y;

25 f)   A motor current size signal 75 from a motor current
          sensor 74;
    g)   a leak signal 91 from a leak sensor 90.

18

Component and function list:

1   sub-sea reservoir.

2   survey station (2a,..,
2n) on benchmark 6 on
seabed 14.

3   gravity sensor system
comprising gravity
sensor 10.

4   ROVDOG comprising 3 and
depth (pressure) sensors
12.

5   ROV.

6   benchmark on seabed 14.

7   surface (or submarine)
vessel.

8   survey area.

9   Fixed reference station
with respect to the
seabed 14r.

10 gravity sensor.

11 relative gravimetric
measurements (11a,
..,11n).

12 depth sensor.

13 relative depth
measurements (13a, ..,
13n.

14 local survey area sea-
bed (14a, ..,14n).
reference station sea-
bed (14r).

15 relative depth values
(Δd) or (15_2, ..,15_m)

16 clock (16)

17 *separate depth meter
(17r)*

18 short-term local
reference station.

19 short-time local
reference depth
measurement series.

20

21 corrected gravity values
(21a, 21b, ..., 21n).

22 quartz pressure gauges

23 pressure measurements
(23a, 23b, ..., 23n).

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30 microcontroller.

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32

33 difference of relative
depth values (Δd) or

($\Delta33_2, \Delta33_3, .., \Delta33_m$).

34 water-tight housing.

35 thermal isolation.

36x,y double-gimbal
frames orthogonally
arranged.

37x,y x-axis, y-axis 37x,
37y.

38 actuators 38x, 38y for
gimbal frames 36x, 36y.

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51 ROV umbilical cable

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53 ROVDOG umbilical cable

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60 temperature sensor.

61 temperature signal from
60.

62

63

64 coarse tilt sensor.

65 coarse tilt signal from
64.

66

67

68 fine tilt sensor.

69 fine tilt signal from
68.

70 ambient temperature
sensor.

71 ambient temperature
signal from 70.

72

73

74

75

76

77

78

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19

80	motor-driven lead screw 80x, 80y.
81	
82	linear potentiometer 82x, 82y monitoring 80x, 80y.
83	readout 83x, 83y from 82.
84	signal conductor 84x, 84y.
85	
86	
87	
88	control device.
89	
90	leak sensor.
91	leak signal from 90.

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C l a i m s

1.   A method for monitoring possible subsidence of a sea-
bed (14) of a survey area (8) e.g. caused by compaction of
an underground hydrocarbon reservoir (1),
comprising the following steps:
*   conducting at least two measurement series
($S_1, .., S_i, .., S_m$) each comprising at least one time-indexed
depth measurement (13a,13b,.. ,13n), with a separation in
time Δt between the at least two measurement series on the
order of months or years;
*   conducting each depth measurement (13a,13b,..,13n) on a
survey station (2a,2b,..,2n) arranged on a benchmark (6a,6b,
..,6n) having fixed vertical and horizontal position re-
lative to the local sea-bed (14a,14b,..,14n);
*   within each measurement series (S_i), conducting at
least one stationary time-indexed short-time local reference
depth measurement series (19r) on at least one short-term
local reference station (18r) on at least one benchmark (6),
for correcting each depth measurement (13a,13b,..,13n) for
short-time (e.g. tidal) depth variations;
*   conducting the depth measurements (13,19r) relative to
at least one depth measurement (13r) at a reference station
(9) arranged on the seabed (14r) outside the survey area (8)
at least once during each measurement series (S_i), the
reference station (9) essentially being unaffected by long-
term effects taking place due to compaction in the reservoir
(1) during the series of measurements ($S_1, .., S_i, .., S_m$).

2.   Method according to claim 1, comprising
interpreting a difference of relative depth values (Δd) or
($15_2, .., 15_m$) having occured during the time (Δt) in terms of
compaction in the reservoir (1).

3.   Method according to claim 1, the time between at least
the first and the latest measurement series ($S_1, .., S_m$) being
characteristic of a significantly detectable change of
seafloor elevation due to compaction to take place in the
reservoir (1).

4.   Method according to claim 1, the depth measurements
(13a,13b,..,13n) being deducted from pressure measurements
(23a, 23b, ..., 23n).

5.   Method according to claim 1, the stationary short-time
local reference depth measurement series (19r) being
continuous.

6.   Method according to claim 1, the reference station (9)
essentially being close to the survey area (8) and situated
at a depth comparable to the depth of the survey area.

7.   Method according to claim 1, comprising
the stationary short-time local reference depth measurement
(19r) series being conducted by at least one separate depth
meter (17r).

8.   Method according to claim 1 or 7, comprising
at least one stationary short-time local reference depth
measurement (19r) series being conducted at a short-term
local reference station (18r) being identical to or co-
located with the reference station (9) arranged on the
seabed (14r) outside the survey area (8).

9.   Method according to claim 1, 7 or 8, comprising
arranging preferably three or more separate depth meters
($17r_1, 17r_2, 17r_3$) at separate short-term reference stations
($18r_1, 18r_2, 18r_3$) distributed geographically over the survey
area (8) to monitor the tidally varying series of depth
measurements (19r), using the separate continuous and time
indexed depth measurement series ($19r_1, 19r_2, 19r_3$) with a
tidal model for interpolating the local tidal depth for
correcting each time-indexed depth measurement (13) at each
station (2).

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10. A method according to one of claims 1-9, further comprising the following steps:

*   including, in at least two of the measurements series $(S_1, .., S_i, .., S_m)$, relative gravmetric $(11a, 11b, .., 11n)$ measurements simultaneously with the depth measurements $(13a, 13b, .. , 13n)$;

*   conducting each gravity measurement $(11a, 11b, .., 11n)$ on the survey stations $(2a, 2b, .., 2n)$ arranged on the benchmarks $(6a, 6b, .., 6n)$;

*   conducting the gravity measurement (11) relative to at least one reference gravity measurement $(11r)$ at the reference station (9);

*   correcting the relative gravimetric measurements (11) for the corresponding long-term and short-term relative depth measurements $(13, 19r)$ producing depth corrected relative gravity values $(21a, 21b, ..21n)$;

*   correcting the relative gravity values (21) for the effect of seabed subsidence $(15_2, .., 15_m)$ as calculated on the basis of the relative depth measurements $(13a, 13b, .., 13n)$ during the long-term time Δt;

*   interpreting a difference of depth corrected relative gravity values (Δg) or $(\Delta 21_2, \Delta 21_3, .., \Delta 21_m)$ having occured during the long-term time (Δt) in terms of parameters representing a mass density change and/or a mass displacement in the reservoir (1).

11. A method according to claim 5, in which during each measurement series $(S_1, S_2, .., S_m)$ the gravity sensor (10) and the depth sensor (12) are arranged with a fixed relative elevation in their operational position on the station $(2, 9, 18)$.

12. A method according to claim 5, in which the gravity sensor (10) and the depth sensor (12) are carried by means of an ROV (5) from one station $(2, 9)$ to another station $(2, 9)$ between one pair of a relative gravimetric and depth measurements $(11, 13)$ and the next pair of a relative gravimetric and depth measurement $(11, 13)$ in one measurement series (S).

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13. A method according to claim 12, in which the ROV (5) is separate from the gravity sensor (10) during each relative gravimetric measurement (11) in order not to affect the gravimetric measurment (11).

14. A method according to claim 12 or 13, in which the relative gravimetric measurement (11) from the gravity sensor (10) and the depth measurement (13) from the depth sensor (12) are transferred to the ROV (5).

15. A method according to claim 14, in which the relative gravimetric (11) and depth measurements (13) are transferred via an ROV umbilical cable (53) to a surface vessel (7).

16. A method according to claim 10, in which the gravimetric measurements (11) are time-indexed and corrected for the gravity sensor's (10) drift with respect to time by other time-indexed gravimetric measurements (11, 11r) taken before and/or later with the same gravity sensor (10) at a survey station (2) or reference station (9,18) during the same actual period of time (t_i), giving drift-corrected gravimetric measurements (11_t) for further processing to produce corrected gravity values (21).

17. A method according to claim 4, characterized in that the depth measurements (13) arise from pressure measurements (23) converted according to the actual water density and optionally to the measured water density distribution depth profile.

18. Device for monitoring possible subsidence of a seabed
(14) of a survey area (8), and gravity changes in an
underlying petroleum reservoir, comprising the following
features:
*   a depth sensor (12), adapted for being carried by an
ROV (5), to be placed on survey stations (2) on benchmarks
(6) at the seabed (14) for conducting depth measurements
(13);
*   a water-tight pressure housing (34) with a gravity
sensor (10) for making relative gravity measurements (11);
        in which the gravity sensor (10) and the depth sensor
(12) are arranged in a mutually fixed elevation in their
operational position, and adapted for being carried by means
of an ROV (5) from one seabed station station (2, 9) to
another seabed station (2, 9) between one pair of a relative
gravimetric and depth measurements (11,13) and the next pair
of a relative gravimetric and depth measurements (11,13).

19. Device according to claim 18, the depth sensor (12)
comprising quartz pressure gauges (22).

20. Device according to claim 18, the number of pressure
gauges (22) being three.

21. Device according to claim 18, comprising a clock (16)
for time-indexing the depth measurements (13).

22. Device according to claim 21, comprising double gimbal
frames (36x,36y) orthogonally arranged for adjusting the
verticality of the gravity sensor (10) around two axes (37x,
37y).

23. Device according to claim 22, comprising actuators
(38x,38y) for turning the gravity sensor (10) in the gimbal
frames (36x,36y);

24. Device according to claim 21, comprising coarse and
fine tilt sensors (64,68) for giving a coarse and fine tilt
signal (65,69) for the deviation from verticality for the

gravity sensor (10);

25. Device according to claim 21, comprising a signal cable (53) between the depth sensor (12) and the gravity sensor (10), and the ROV (5), arranged for transmitting the depth measurement (13) and the relative gravity measurement (11) from the sensors (10,12) to the ROV.

26. Device according to claim 25, the signal cable (53) also conducting the tilt signals (65,69) from the tilt sensors (64,68) of the gravity sensors to the ROV (5).

27. Device according to claim 18, at least the gravity sensor (10) adapted for being released from the ROV (5) during each relative gravimetric measurement (11) in order not to be disturbed by the ROV (5).

28. A device according to claim 18, in which the relative gravimetric measurement (11) from the gravity sensor (10) and the depth measurement (13) from the depth sensor (12) are transferred to the ROV (5) by an umbilical cable (53).

29. A device according to claim 14, in which the relative gravimetric (11) and depth measurements (13) are transferred via an ROV umbilical cable (51) to a surface vessel (7).

30. A benchmark (6) for providing a measurement station (2) providing support for depth and/ or gravity meters (12,10), comprising:
        an extending structure with a plane top surface constituting the measurement station (2) adapted for extending above the surface of unconsolidated sediments of the seabed; and
        the extending structure based on a central portion of a base plate being heavy while submerged in water and adapted to settle in a horizontal position in the unconsolidated sediments for stabilizing in deeper sediments;
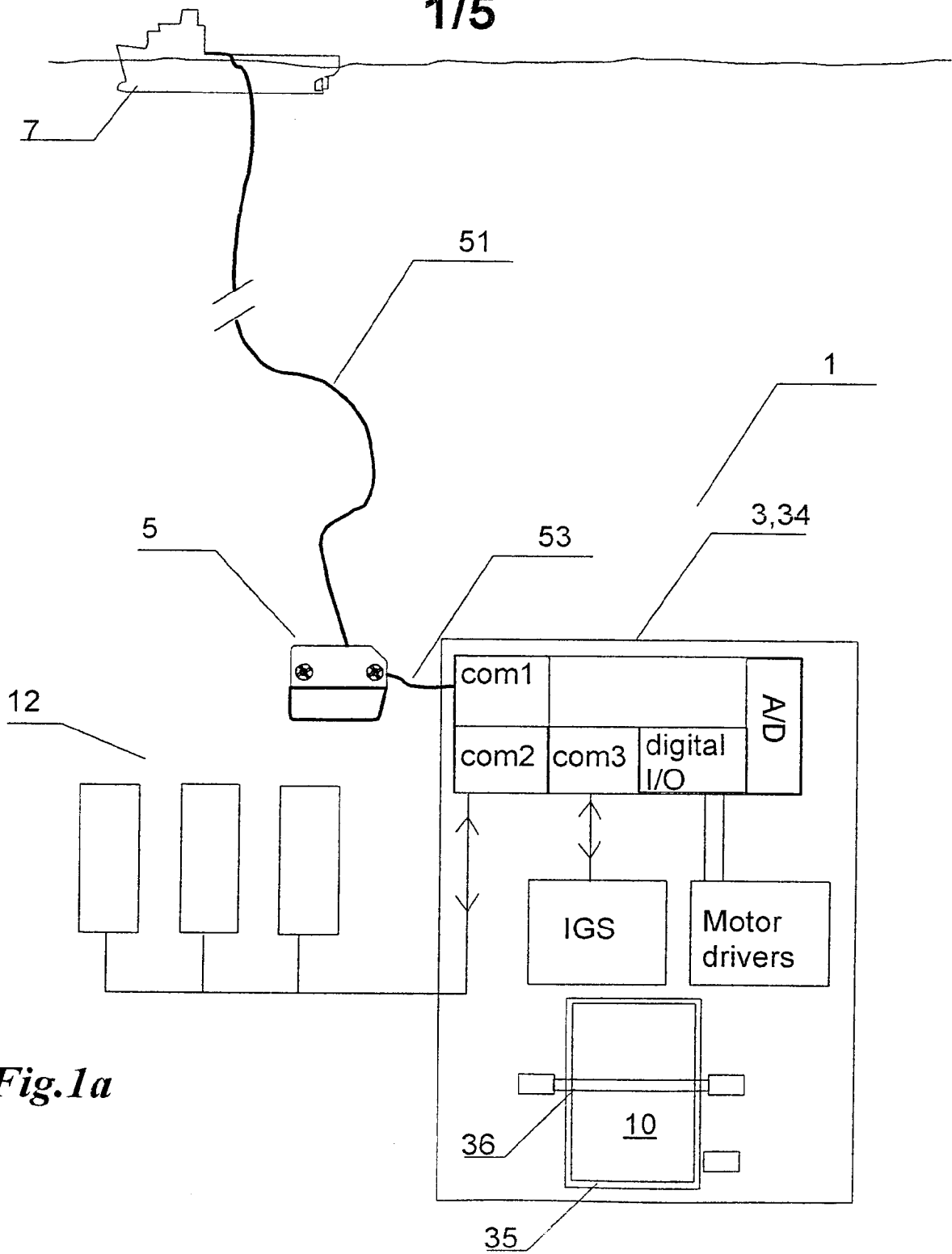   at least the base plate being perforated for avoiding entrapment of fluids and allowing fluids to escape.

AMENDED CLAIMS
[received by the International Bureau on 11 May 2001 (11.05.01);
original claim 30 cancelled;
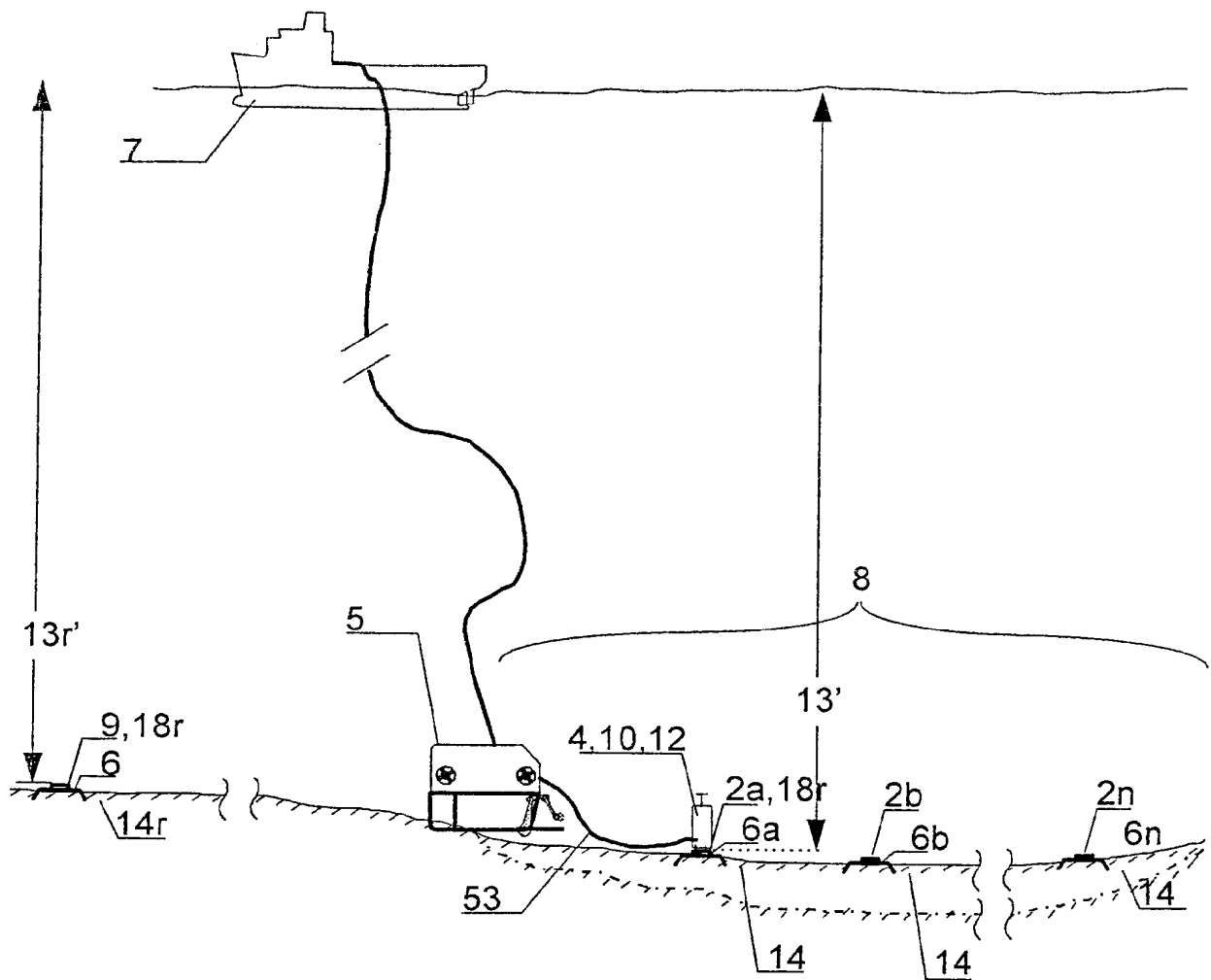remaining claims unchanged (1 page)]

29. A device according to claim 14, in which the relative
gravimetric (11) and depth measurements (13) are transferred
via an ROV umbilical cable (51) to a surface vessel (7).

7

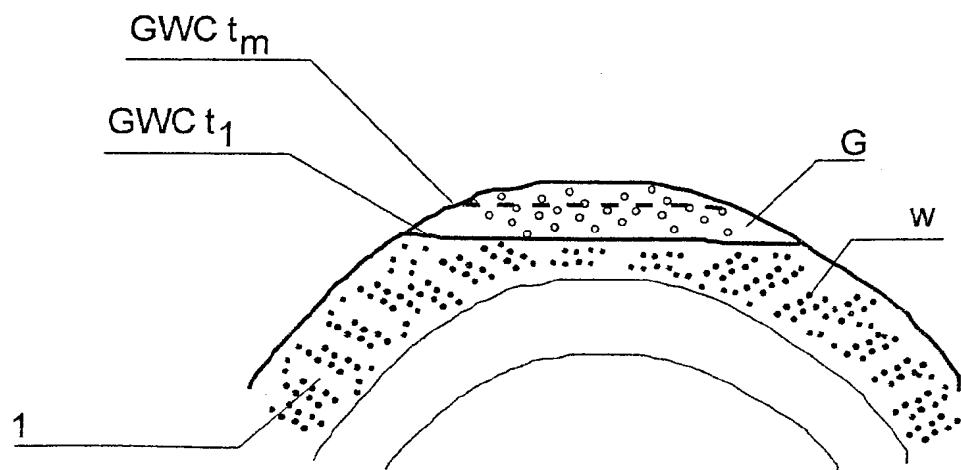51

1

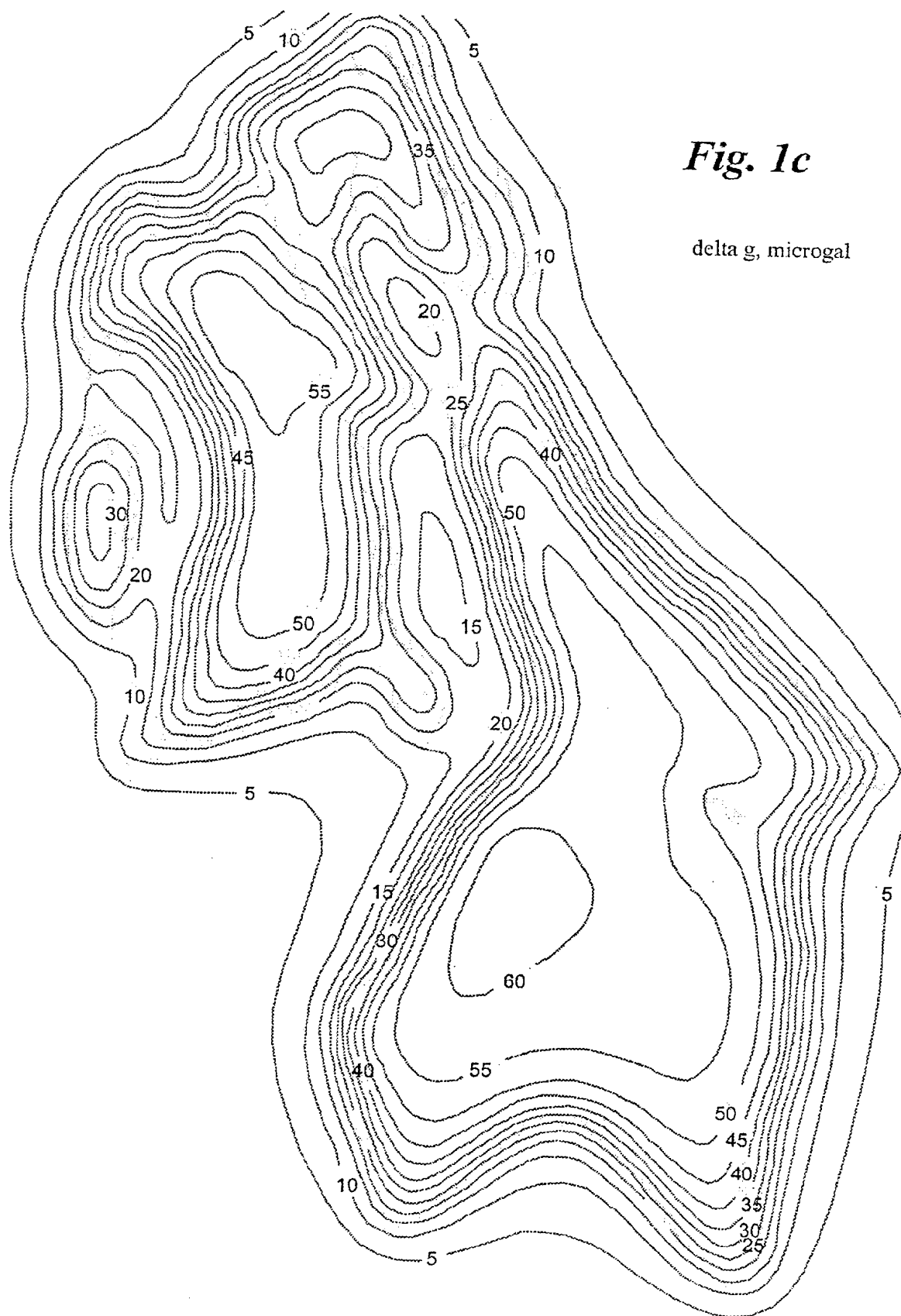5   53   3,34

12

com1

com2   com3   digital
                I/O

A/D

IGS   Motor
           drivers

36   10

35

Fig.1a

Fig.1b

Fig. 1c

delta g, microgal

Fig.2

$$m \text{ series: } \begin{Bmatrix} S_1 \\ S_2 \\ \cdot \\ \cdot \\ \cdot \\ S_m \end{Bmatrix} = \begin{pmatrix} 11a_1,13a_1 & 11b_1,13b_1 & 11n_1,13n_1 \\ 11a_2,13a_2 & 11b_2,13b_2 & 11n_2,13n_2 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ 11a_m,13a_m & 11b_m,13b_m & 11n_m,13n_m \end{pmatrix}$$
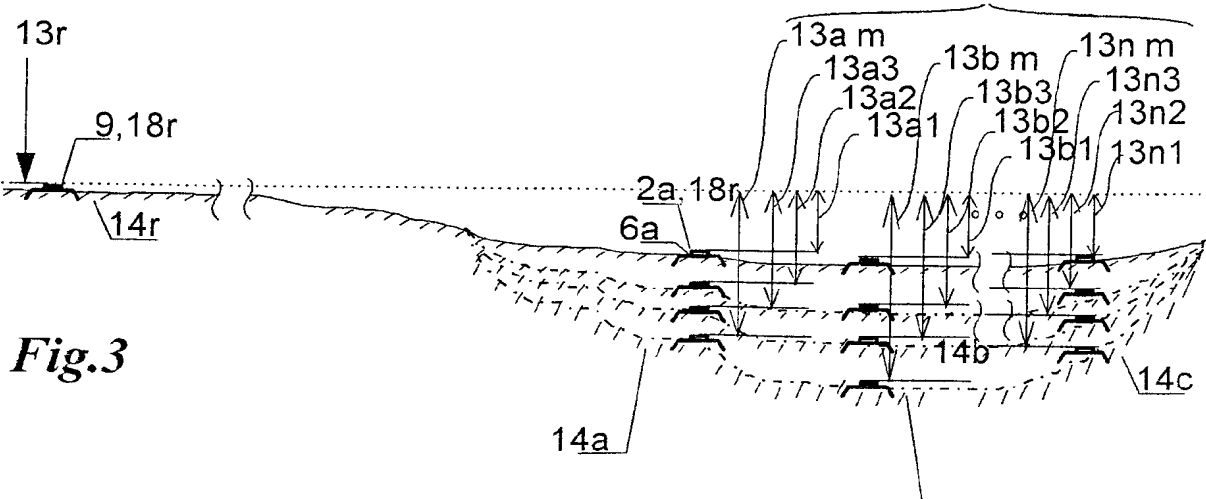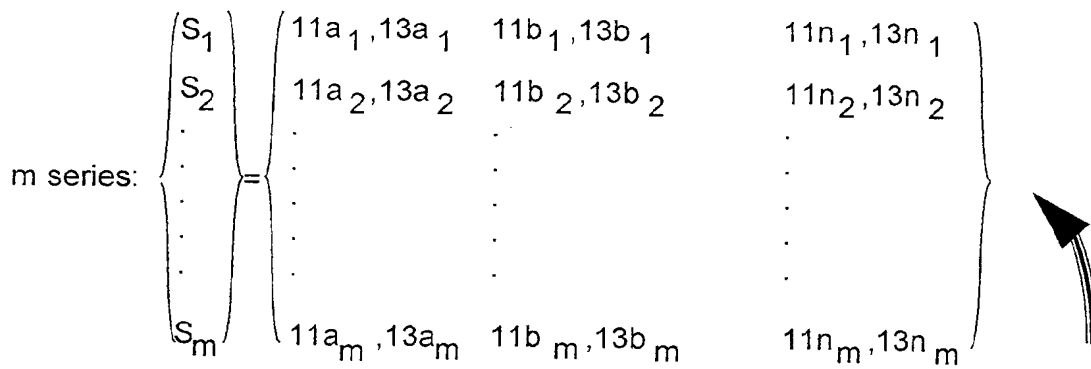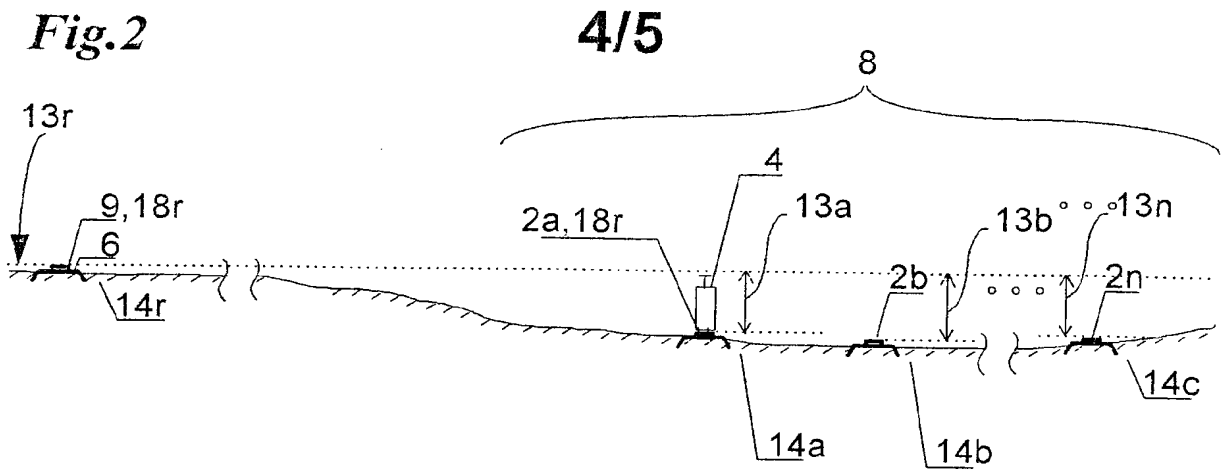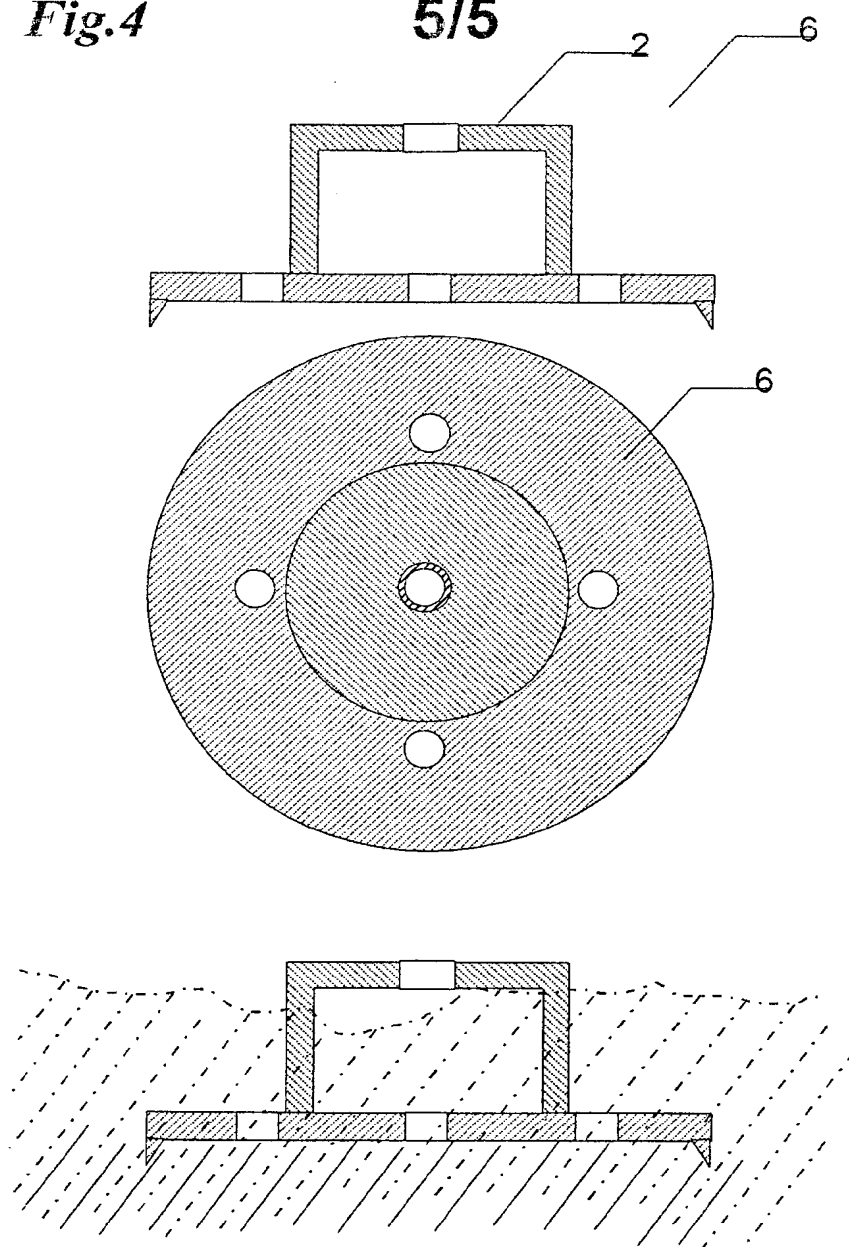

Fig.3

Fig.4   **5/5**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/NO 00/00425

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: G01V 9/00, G01C 13/00
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: G01V, G01C, E21B, G01F, E02D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5753813 A (T.HAGIWARA), 19 May 1998 (19.05.98), column 3, line 40 - column 4, line 67 --	1-30
A	US 5791187 A (HAK SOO CHANG), 11 August 1998 (11.08.98), column 3, line 54 - line 66, abstract --	1-30
A	US 5615114 A (PER-GUNNAR NORDIN), 25 March 1997 (25.03.97), column 3, line 62 - column 4, line 65 --	1-30
A	US 5198820 A (P.GRAEBNER), 30 March 1993 (30.03.93), column 1, line 42 - column 2, line 12 --	1-30

[X] Further documents are listed in the continuation of Box C.　　[X] See patent family annex.

*	Special categories of cited documents:
"A"	document defining the general state of the art which is not considered to be of particular relevance
"E"	earlier application or patent but published on or after the international filing date
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O"	document referring to an oral disclosure, use, exhibition or other means
"P"	document published prior to the international filing date but later than the priority date claimed

"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X"	document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y"	document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 March 2001	2 0 -03- 2001
Name and mailing address of the ISA/ Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. + 46 8 666 02 86	Authorized officer Gordana Ninkovic´ /itw Telephone No. + 46 8 782 25 00

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/NO 00/00425

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5218864 A (K.A.PENNYBAKER), 15 June 1993 (15.06.93), column 2, line 56 – column 3, line 15 --	1-30
A	JP 11351866 A (HAZAMA GUMI LTD)1999-12-24 (abstract).(online)(retrieved on 2001-03-14) Retrieved from: EPO PAJ Database; & JP 11-351866 a (HAZAMA GUMI LTD)	1-29
P,X	abstract -- --------	30

International application No.
25/02/01	PCT/NO 00/00425

Patent document cited in search report			Publication date	Patent family member(s)			Publication date
US	5753813	A	19/05/98	NONE			
US	5791187	A	11/08/98	CA	2171801	A	11/01/97
				DE	19620656	A,C	16/01/97
				JP	2855423	B	10/02/99
				JP	9236473	A	09/09/97
				KR	185260	B	15/05/99
				RU	2124702	C	10/01/99
				KR	138943	Y	01/05/99
US	5615114	A	25/03/97	US	5001634	A	19/03/91
				US	5602731	A	11/02/97
				DE	3768089	D	00/00/00
				DK	392088	A	22/08/88
				EP	0294464	A,B	14/12/88
				SE	0294464	T3	
				NO	883140	A	14/09/88
				WO	8804784	A	30/06/88
US	5198820	A	30/03/93	NONE			
US	5218864	A	15/06/93	NONE			